Heat Transfer Characteristics During Cryoablation

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Technology

in

Biomedical Engineering

by

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May 2012

Dedicated to my family

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Certificate

This is to certify that the work in the thesis entitled ***Heat Transfer Characteristics During Cryoablation*** by ***Lokesh K A*** in partial fulfillment of the requirements for the award of the degree of Master of Technology in Biomedical Engineering during session 2011-2012 in the Department of Biotechnology and Medical Engineering, National Institute of Technology Rourkela is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Place: NIT Rourkela
Date: 31 May 2012

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Lokesh K A

Abstract

In the present study, the overall heat transfer coefficient of Zacarian disc in different media is investigated experimentally and predicted numerically. Copper disc is chosen for the study because of its high heat capacity; a property by which a material can withstand the heat for a longer time. In dermatology, heat transfer rate of the disc at the skin surface plays a crucial role for the necrosis of the tumour while applying the cryogen. The disc immersed in liquid nitrogen can be directly applied on to the tumour surface for the ablation of tumour. Cryoablation of tumour occurs by the formation of ice crystals within cells and the cellular metabolism gets affected which leads to the apoptosis of the cell. The cooled disc was allowed to thaw in different media viz. air, water, and gel. The formation of ice and maximum penetration were studied when the sub-cooled disc was exposed in water and gel. To mimic biological skin tissue, 0.2% agarose gel was used. Heat transfer characteristics for the biological skin tissue were studied. The overall heat transfer coefficient between the disc and air was found to be 19.5 W/m^2K while it is 65.5 W/m^2K for a system consisting of disc and water.

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Chapter 1

Introduction

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Introduction

1.1 Introduction

Cryoablation is a process where undesirable tissues are removed employing extreme cold temperatures. This technique was approved by the United States Food and Drug Administration (FDA) in 1999. When cryogens are applied on to the tumour surface extracellular ice formation starts followed by the intracellular ice formation. As the ice crystals grows in the size cell membrane ruptures and leads to the apoptosis of the cell. This technique is widely used in various medical fields, e.g. dermatology, oncology, gynaecology, neurosurgery, etc.

Cryoablation of tumour can be done by

1. Cotton swab method
2. Zacarian disc
3. Cryoprobe
4. Cryospray.

In Cotton swab method, liquid nitrogen is directly applied to the tumour surface using a cotton swab. This technique can only be used for surface skin tumours. In Zacarian copper disc method, copper disc is immersed in liquid nitrogen and applied to the tumour surface. This technique provides deeper penetration than the cotton swab method. In cryoprobe method, cryoprobes are inserted inside the tumour. The cryoprobe is cooled by the liquid nitrogen which circulates inside it and in turn apoptosis occurs. This technique can be used for the treatment of prostate cancer, oesophageal cancer, etc. Cryospray ablation is a new ablation technique offering the physician to treat focal and broad lesion. In this approach, liquid nitrogen is sprayed onto the tumour surface.

The overall heat transfer coefficient (U) is one of the important parameter which decides the extent of damage of the tumour. So it is very essential to investigate the heat transfer rate of the Zacarian disc at the skin surface.

1.2 Historical Review

The term cryotherapy was derived from the Greek word *kruos* which means cold and therapy means cure. The Cryoablation technique has gone through a long term process of development.

Ancient

The ancient Egyptians (3500 years ago) were aware of the anaesthetic and anti-inflammatory properties of cold, and they used it for the treatment of infected wounds. Hippocrates, the father of modern medicine described the clinical usage of cold to relieve pain in wounds and joints. In 11^{th} century, Avicenne used ice as an anaesthetic agent. In 1650s, Whenry used ice for the treatment of gout. In 1661, Thomas Bartholin described the usage of cold as a therapeutic agent for all types of everyday illnesses.

Mid-19^{th} century

However the use of sub$-$zero temperature for the treatment of the skin tumours was not familiar till 19th century. In Mid-19^{th} century James Arnott [1], a Britain physician was the first person who used extreme cold for destruction of tissue. He used a mixture of sodium chloride (NaCl) and crushed ice for the treatment of breast cancer and uterine cancer. He recognised the analgesic effect of cold and recommended the use of cold as an anaesthetic before the operation. He developed a water cushion for the treatment of surface tumours, which contains a solution that freeze on the lesion surface. He was able to achieve temperatures of $-24°C$. After thawing the tumour became less visible.

Late 19^{th} century

The usage of liquid air and carbon dioxide (CO_2) as cryogens was popularised in the late 1870s. Louis Paul Cailletet [2] successfully produced liquid oxygen and liquid CO_2 by cascade process in 1877. In 1895, Carl von Linde succeeded in the liquefaction of air. Campbell White [3, 4], a physician of New York, was the first person who employed refrigerants for clinical use. He recommended that liquid air can be used for the treatment of different diseases, including herpes, nevi, warts, varicose leg ulcers, etc. Storage of cryogenic fluids was a concern in that time. This led to the development of the first vacuum−jacket vessel for the storage of cryogenic fluids in 1892 by James Dewar [5]. This vessel greatly prevented the evaporation of the cryogenic fluids.

The first cryospray medical usage was done by Whitehouse [6] in 1907. The liquid air was sprayed onto the tumour surface. In the same year Pusey William [7] successfully used solid carbon dioxide; this was a milestone towards the establishment of cryotherapy. In 1940s, Kapitsa and Collins found out an effective way for the production of liquid nitrogen.

Mid−20^{th} century

In 1950, Allington [8] was the first to use liquid nitrogen. He used a cotton swab for the treatment of various benign lesions but the heat transfer between the cotton swab and the skin was very poor. So this method was insufficient for tumour treatment.

Irving S. Cooper [9] designed a liquid nitrogen probe in 1963, which was able to achieve temperatures up to $-196°C$. He treated Parkinson's disease and other disorders by freezing the thalamus. Imaging techniques like X-ray helped Cooper to place cryosurgical probe accuaretly. Freezing of the tumour occurred at $-10°C$ and he performed brain cryosurgery successfully. Setrag A. Zacarian's [10, 11] contribution towards the field of cryoablation was vital. He developed two kinds of equipment: one was a commercial-grade spray which contains a spray bottle, which produces a very narrow, consistent spray. The other was a copper disc probe (which in turn termed as Zacarian copper disc) that allowed freezing of tissue approximately 7 mm below the skin surface. In 1970, Zacarian donated handheld cryosurgical unit to the Oxford dermatology department. Hence Oxford became the center of cryosurgical research for Britain and Europe. During the 1980s, advancement in the imaging techniques such as nuclear magnetic resonance (NMR), computerized tomography (CT) and ultrasound, etc. helped the surgeons to monitor the freezing extent during cryosurgery.

Late-20^{th} century to present

In the 1990s, open cryosurgery was performed by Zhou [12, 13] with liquid nitrogen for the treatment of hepatocellular carcinomas. Almeido Gongalves introduced multiprobe argon$-$helium system for cryoablation in mid 1990s. In 1999 cryoablation technique was approved by United States, Food and Drug Administration (FDA).

Today, cryoablation is applied for the treatment of tumours in the bone, skin, brain, retina, prostate, and uterus. Renal tumour cryoablation was done by Uchida (Japan) in 1995 [14]. In 1997, Staren et al [15] performed breast cryosurgery in small and large animals. Cryoablation of pancreatic cancer was carried out by Kovach [16] in 2002.

1.3 Skin Tumours And Its Remedy

1.3.1 Structure of human skin

Human skin is composed of three primary layers namely: epidermis, dermis and subcutaneous fat. The outermost layer epidermis is having a thickness of approximately 0.75−1 mm. Epidermis acts as a protective covering of tissue. The second layer is dermis which lies beneath the epidermis. Dermis is associated with blood vessels. Dermis is having a thickness of 2−3 mm. Subcutaneous fat contains adipose cells and fibroblasts and lies beneath the dermis. It is having a thickness of 6−7 mm [17, 18].

1.3.2 Skin tumour

Skin tumours are abnormal growths of tissue. Tumour can be either cancerous (malignant) or harmless (benign).

Types of skin tumour

- Actinic keratosis
- Basal cell carcinoma (BCC)
- Melanoma
- Kaposi's sarcoma
- Squamous cell carcinoma [19]

Actinic Keratosis
It is also called as solar keratosis, and found in sun exposed regions of the body. It is having a size of <0.5cm in diameter. It acts as primary lesion for squamous cell carcinoma. Actinic keratosis is caused by being in sunlight.

Basal cell carcinoma
Basal cell carcinoma is a slow-growing form of skin cancer. BCC starts in the epidermis and it keeps on growing. It is caused by regular exposure to ultraviolet

radiation and sunlight.

Melanoma

It is the most dangerous type of skin cancer and can cause even death. Melanoma is a cancer that develops in melanocytes. It can spread to the other part of the body. Melanoma is caused by damage from UV light from the sun. Early detection and diagnosis are crucial.

Kaposi's sarcoma

It is a tumour caused by Human herpesvirus 8 (HHV8). It affects the connective tissue, and is often associated with AIDS.

Squamous cell carcinoma

SCC is the epithelial cancer. It is caused by Human papilloma virus (HPV). It can be affected to various parts of the body like oesophagus, lungs, prostrate, head and neck.

Followings are the treatment methods available at present:

1. **Treatment with Acids:** Acids like Bi$-$ or trichloroacetic acid and salicylic acid can be used for the treatment of surface tumours and warts. Advantage of this method is: it is convenient with reasonable cost. Acids are well suited for use in children.

2. **Surgery:** Surgery is done to remove tumour that keeps spreading to other parts of the body. It is the most common method for the treatment of melanoma. Common typez of surgical procedure include,

    - Local excision: Surgery is done to take out the melanoma and a small portion of the tissue surrounding the tumour.
    - Wide local excision: In wide local excision, large portion of the tissue surrounding the melanoma is removed. Lymph nodes may also be removed during this surgery.
    - Lymphadenectomy: Here lymph nodes which are affected by tumour are removed during the surgical procedure [20].

3. **Chemotherapy:** This technique uses anti-cancer drugs to destroy the tumour. This drug kills the actively dividing cells which is the property of the tumour cells. Disadvantage of this method is that it can affect bone marrow cells which divide rapidly under normal condition also. Targeted delivery mechanisms will help the drug to be focussed on to the tumour. Nanoparticles can also be used for the control drug delivery [21].

4. **Radiotherapy:** In this technique high energy rays are used to kill the cancerous cells. It works by damaging the DNA of the cancerous cells. Proton can be used to target the tumour tissue. Radiotherapy is used for the treatment of malignant tumours.

5. **Photodynamic therapy:** Photodynamic therapy uses a drug, called a photosensitizer, and a particular type of light. When this drug is exposed to a specific wavelength of light, it produces a form of oxygen that kills the tumour cells. The limitation of this method is that photosensitizer cannot penetrate more than 1 cm [22].

6. **Cryoablation:**

   - Cotton swab: Liquid nitrogen is directly applied on the tumour surface using a cotton swab. This technique can only be used for surface skin tumours [9, 23].
   - Zaccarian copper disc: Copper disc is immersed in liquid nitrogen is applied on the tumour surface. This technique is having deeper penetration than the cotton swab method [10, 11].
   - Cryoprobe: Cryoprobes are inserted on the tumour surface. Liquid nitrogen is circulating inside this cryoprobe. This technique can be used for the treatment of prostate cancer, oesophageal cancer, etc [24].
   - Cryospray: Cryospray ablation is a new ablation technique offering the physician to treat focal and broad lesion. It consists of a dewar, a delivery pipe and interchangeable nozzles [25, 26].

1.3.3 Mechanism of cryoablation

Cryoablation of tumour occurs by the formation of ice crystals within cells and the cellular metabolism gets affected which leads to the apoptosis of the cell. Cryoablation procedure involves tissue destruction during controlled freezing. Each cell in tissue is subjected to different thermal conditions. The cells nearest to the cryoprobe will have a lowest temperature and fastest cooling rate than the cells far away from the cryoprobe. Thermal history of target tissue plays an important role because different cells will have different cooling temperature at different location. There are five micro scale events that have been the main concern for the tissue injury during the freeze-thaw process, they are:

1. Extracellular Ice Formation (EIF)
2. Intracellular Ice Formation (IIF)
3. Growth of ice crystals
4. Rupture of cell membrane
5. Apoptosis of the cell

When cryogens are applied on the tumour surface, extracellular ice formation occurs followed by the intracellular ice formation. As the time progresses the ice crystals grow in size and leading to the rupture of cell membrane and finally cell death occurs [27, 28, 29].

1.4 Literature Review

1.4.1 Experimental studies on tissue phantoms

The first investigation of tissue temperature field during cryoablation through experimentation was done by Cooper [30]. The tissue phantom used was clear gel made up of 1.5% gelatin and 98.5% water. The temperature field produced by the single liquid nitrogen circulated cryoprobe in the gel was determined.

A gel of 2% gelatin and 98% water was prepared by Budman [31]. He employed cryoprobes of liquid nitrogen and pressurised N_2O. Temperature was measured by thermocouples at different locations. Augustynovvicz [32] also conducted the similar experiments with different gelatin concentrations.

Rabin [33] conducted experiments with 2.5% gelatin and 97.5% water system, which have the same properties of prostrate. K.J. Chua [34] used 0.2% agar gel to study the effect of freezing and thawing in a biological system, because the gel has the similar properties like human tissue. He also conducted the same study using animal model to compare the result.

Andy Tsai [35] prepared a gel of 80% glycerol and 20% agar. This gel was having a thermal conductivity of 0.33 W/$m°K$which matches with the thermal conductivity of skin tissue. Human tissue phantom mimicked by the gel gives a realistic approach for the measurement of temperature at different locations. The results can only deliver a qualitative approach as clinical conditions vary from that of experimental ones.

1.4.2 Experiments on animal / human tissues

In vitro **experiments**

Using fresh bilogical samples (beef liver, porcine liver, etc.) for study yields more encouraging and qualitative results rather than mimicking tissue in the form of gels. In 1984, Onik [36] has performed experiment on beef liver to study the effect of temperature and ice front propagation. In 1985, Augustynovvicz [32] conducted experiment on beef muscle and liver to study the effect of cooling rate and iceball growth with liquid nitrogen cryoprobe. Homasson in 1994 [37] performed an experiment to find out the iceball growth and impedance of rat tissue culture, human serum by liquid nitrogen cryoprobe. In 2000, Yang [38] employed cryoablation on mouse bladder tumor cell line MBT−2 to study the thermal history using liquid nitrogen cryoprobe.

In vivo **experiments**

Real−time monitoring of the thermal history of tumour during cryoablation was done by Brodthagen in 1961. Pivert [39] developed a technique to monitor the temperature of the tissue by impedance method. Zacarian [10, 11] designed a copper disc for the treatment of tumours and he performed cryoablation in humans. Torre [40] conducted cryoablation using liquid nitrogen spray in dogs and he inserted two thermocouples beneath the skin to measure tissue temperature and he concluded that there is no consistent relationship available between the lateral spread and depth of the frozen zone.

Advancement in the imaging techniques helps in real time monitoring of freezing at the interface. Gilbet [41] used ultrasonic techniques in hepatic cryosurgery. Nuclear Magnetic Resonance (NMR) was applied by Rubinsky [42] in the cryoablation of rabbit brain and dog prostate. Magnetic Resonance Imaging (MRI) was applied by Samset [43] in the cryosurgery of pig liver.

In vivo experimental studies give an overview about the cryoablation but it do not give the information regarding the thermal history of target tissue, and the propagation of freezing front on a particular cross-section plane. However, cryoablation requires information on the tissue thermal history, e.g. whether the target tissue attained lethal temperature or not. In addition, cryoablation needs careful planning for the evaluation of thermal history of tissue before the commencement of the cryosurgery. A simulation tool which predicts the thermal history of target tissue and lethal temperature is highly desired.

1.4.3 Thermal modelling of cryoablation

Mathematical modelling of cryoablation helps to determine the thermal history of the tissue in question, thereby helping in successful execution of the procedure. It can determine thermal effects of blood perfusion and metabolism within the tissue before freezing, latent heat liberated during freezing of tissue and conduction of heat within the frozen tissue. The first mathematical model of cryoablation was developed by Comoni [44] in 1976.

1.4.4 Heating of metal during natural convection

Dotson [45] in 1954 studied natural convection heat transfer to air from a vertical aluminium sheet. Liu [46] found out the heat transfer coefficient of the water to be 2400 W/m^2K. Spina [47] performed an experiment to find out convective heat transfer coefficient of water. He prepared a series of mixture having different proportions of silicone oil and water. A thin copper disc attached with thermocouple was used for the experiment. The disc was heated up to 100°C. The temperature values were recorded using National Instruments USB 6212 and the LabVIEW software.

To the authors' best knowledge there is not much literature about the heat transfer coefficient of the disc which is used in dermatology for the cryoablation of tumour. So we planned to design an experimental setup which helps us to study the heat transfer characteristics of the Zacarian disc when thawed in different media like air, water, and gel mimicking skin tissue. The objective of current study is to investigate the heat transfer characteristics of sub-cooled Zacarian disc in different media experimentally and to predict the overall heat transfer coefficient numerically.

Chapter 2

Materials and Methods

Chapter 2

Materials and Methods

2.1 Materials

- Agarose powder (HIMEDIA): The gels made of agarose are having a thermal conductivity close to that of skin tissue.
- Copper disc: Copper disc of 20 mm diameter and height of 40 mm was used in the experiment. Due to high heat capacity of copper it can withstand the heat for a longer time.
- K-type thermocouple (Chromel-Alumel): K-type thermocouples are used for general laboratorial purpose. Thermocouples are available in the range of -200°C to +1200°C. Sensitivity is approximately equal to $41\mu V/°C$.
- Distilled water: In chemical and biological laboratories distilled water is preferred to carry out the experiments.
- Advantech portable data acquisition module (USB-4704): It is used as an interface between the thermocouple and the computer. Real time monitoring of temperature is achieved by the data acquisition module.

2.2 Methodology

Preparation of the Gel:

0.2% agarose gel was used in our experiment, because the thermal conductivity of the gel mimics the human skin-tissue. The gel was prepared by mixing 0.2 grams of agarose powder (HIMEDIA) in 100 mL of distilled water and then flask was kept in the microwave oven. The solution was heated (about 2-3 minutes) till it becomes completely clear, i.e. no small floating particles were visible. During the heating, the flask was frequently stirred to mix the solution homogeneously. After that the solution was allowed to cool until solidified.

Copper disc was attached to a wooden handle for the ease of handling. K-type thermocouple was brazed on the surface of the copper disc. The Zacarian disc, initially at room temperature of $36°C$, was cooled to different temperatures by immersing it in liquid nitrogen. The temperature response was recorded using data acquisition system and LabView.

2.3 Experimental setup

For our experiment, we need to measure the overall heat transfer coefficient of thawing of a Zacarian copper disk through different media viz. air, water, and gel mimicking skin tissue. 0.2% agarose gel is used which mimics the skin tissue. Figure 2.1 represents the schematic diagram of the experimental setup.

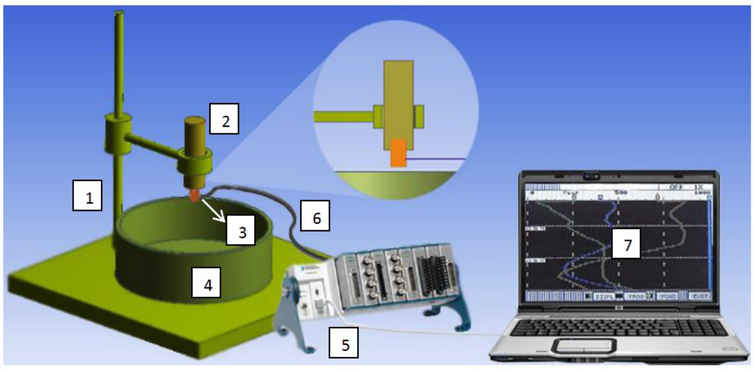

Figure 2.1: Experimental setup.

1. Holder
2. Wooden handle
3. Copper disc (Φ 20 mm $and\,height$ 40 mm)
4. Sample
5. Data acquisition system
6. Thermocouple
7. Computer

It consists of a Copper disc attached to a wooden handle which is held by means of a holder. The thermocouple is brazed on the surface of the copper disc is connected to an advantech portable data acquisition module (USB-4704) which intern connected to a computer. Online monitoring of temperature is done using LabVIEW.

A copper disc having a diameter of 20 mm and a length of 40 mm was chosen for the experiment. Copper was preferred because of its high heat capacity to withstand the heat for a longer time. K−type thermocouple was brazed at the edge of the disc. Temperature values were recorded using Advantech portable data acquisition module (USB-4704)[47, 48].

2.4 Temperature measurement using Advantech portable data acquisition module (USB-4704)

Thermocouple acts as a transducer which converts the temperature variations to variations in the voltage. These voltage variations are acquired using an Advantech portable data acquisition module (USB-4704). The voltage values detected in the data acquisition module are in the range of millivolt (mV) and are easily susceptible to noise.

So an easy and efficient method to find the voltage value with more accuracy is finding the Arithmetic mean which effectively calculates the mean of 1000 samples; we sampled the data at a rate of 1000 samples/sec.

If N is the number of samples we took in one second

The arithmetic mean is given by $\sum\limits_{i=1}^{N} \frac{V_i}{N}$.

More the number of samples more precise will be the voltage value. The voltage values are then stored by using write measurement file.

2.5 Calibration of thermocouple

The thermocouple was calibrated for two different temperatures. One with air−oven which was maintained at $37°C$ and other with a deep−freezer, maintained at

$-20°C$. Thermocouple was inserted into the air$-$oven and the temperature was measured using thermocouple. Thermocouple was showing the precise temperature with an error of $\pm 2°C$. Same procedure was repeated for the deep$-$freezer also.

2.6 Performing the experiment

Copper disc was cooled to different temperatures and allowed to thaw in different media. Real time monitoring of temperature was done. Overall heat transfer coefficient was found out for different media using numerical modelling.
Table 2.1 shows the different media used in the experiment. The sub-cooled copper disc is exposed to the medium through two surfaces: the circular area at the base (represented by medium 2) and the curved area of the disc (represented by medium 1).

Table 2.1: Different media used for the experiment

Medium1	Medium2
Air	Air
Air	Water
Air	Gel

Chapter 3

Results and Discussions

Chapter 3

Results and Discussion

When the sub−cooled copper disc is exposed to different media, heat transfer occurs by convection from the surface of the disc. Investigations are carried out to study the overall heat transfer coefficient of the sub−cooled Zacarian disc. The Zacarian disc is sub−cooled to $-40°C$, $-75°C$,$-100°C$, and $-145°C$ from room temperature of $36°C$ by immersing it in liquid nitrogen; the sub−cooled disc is then thawed in room air. The temperature response is recorded using data acquisition system and LabView. Numerical modelling is carried out to study the overall heat transfer coefficient when the sub−cooled Zacarian disc is thawed in air and the numerical and experimental results are compared. The overall heat transfer coefficient which predicted the temperature profile more closely to the experimental observation is considered to be the overall heat transfer coefficient for the given system. Similar studies have been carried out when the sub−cooled Zacarian disc is exposed to water and gel.

3.1 When sub−cooled Zacarian disc is exposed to air

Figure 3.1 shows the temperature profile of the sub−cooled Zacarian disc when exposed to air. In the figure T_i represents the initial temperature of the sub−cooled disc. It is observed that the time taken for the disc to attain room temperature gradually increases with the decrease in initial temperature. This is happening because with the decrease in initial temperature, the formation of ice layer over the disc surface increases and also the thermal conductivity of the air decreases with the decrease in temperature (represented in table 3.1); these two factors together increases the thermal resistance and consequently heat transfer decreases. It is also interested to observe that temperature variation is almost linear except for lower value of initial temperature of the disc.

Table 3.1: Thermal conductivity of air at different temperatures

Temperature ($^{\circ}C$)	Thermal Conductivity of air(W/mK)
0	0.0243
−50	0.0204
−100	0.0160
−150	0.0116

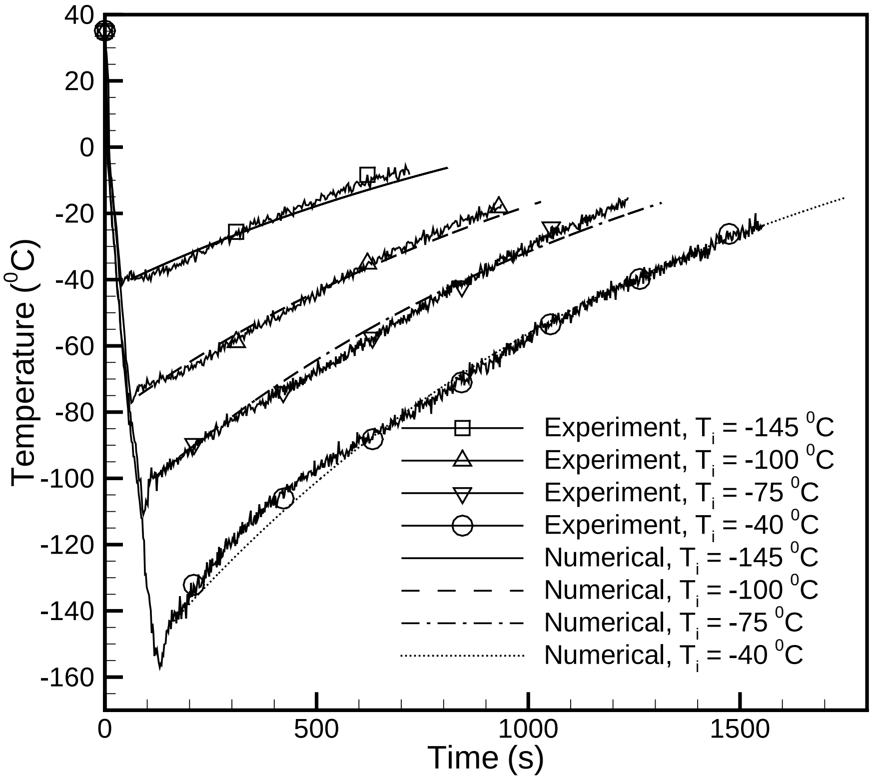

Figure 3.1: Temperature profile of sub−cooled Zacarian disc when exposed to air.

The result obtained with the numerical model is also plotted in the figure. It can be noticed that the temperature values obtained by numerical model match reasonably well with the experimental values. The overall heat transfer coefficient was found out to be 19.5 W/m^2K.

3.2 When sub−cooled Zacarian disc is exposed to water

Figure 3.2 shows the temperature profile of the sub−cooled Zacarian disc when exposed to water. The initial temperatures of sub−cooled disc are $-39°C$, $-90°C$, and $-122°C$. It is quite obvious that disc sub−cooled to $-39°C$ thawed more rapidly than the disc sub−cooled to $-122°C$. It is also interesting to observe that temperature profile is not linear as compared to the case when disc was exposed to air. Moreover, the time taken to reach the room temperature is also less for this case compared to the respective case of air. Since, the thermal conductivity of water is quite high as compared to that of air, the overall thermal resistance decreases; consequently, thawing of sub−cooled disc is more rapid.

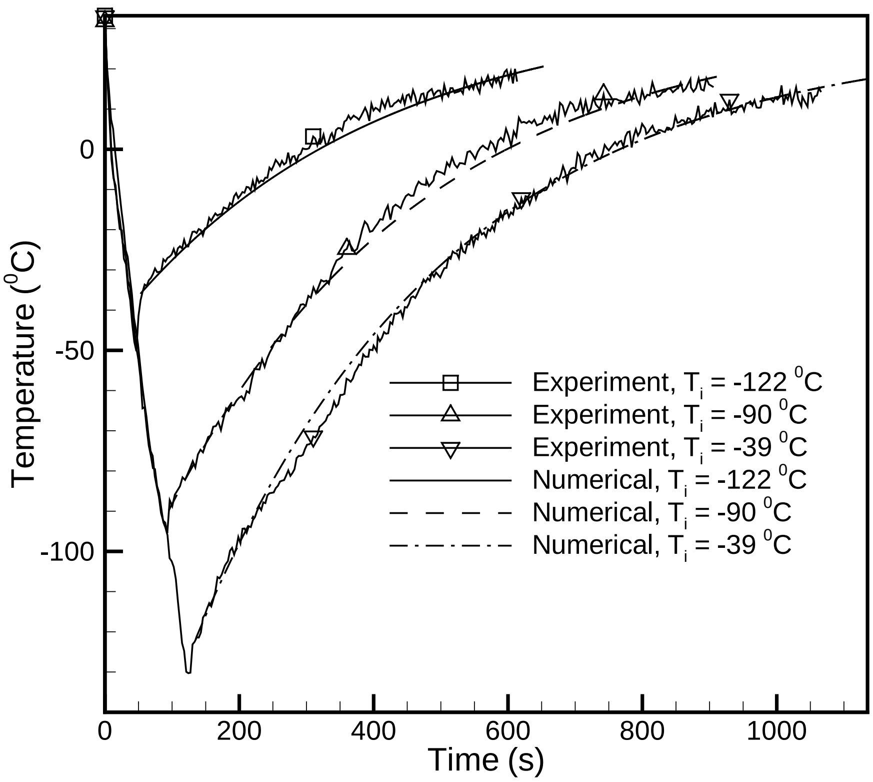

Figure 3.2: Temperature profile of sub−cooled Zacarian disc when exposed to water.

The result obtained with the numerical model is also plotted in the figure. It can be noticed that the temperature values obtained by numerical model match reasonably well with the experimental values. The overall heat transfer coefficient was found out to be 65.5 W/m^2K.

The sub$-$cooled disc is exposed to water through bottom part of the disc which acts as a heat sink. The disc absorbs the latent heat of water, as a result, the water in contact with the disc transforms into ice which grows with time. The increase in ice volume continues till the heat absorbed by the disc at the water$-$disc interface is more compared to the heat supplied by the surrounding water at the water$-$ice interface. The ice volume attains a maximum value followed by decrease in its value, because of melting of ice, till it vanishes completely. The ice starts melting because of the more heat supplied at the water$-$ice interface than the heat released through the disc at water$-$disc interface. Figures 3.3$-$3.5 present the shape of ice ball formed at its maximum value. Since the disc is placed symmetrically in the water, the symmetry of ice ball is quite obvious. However, the ice volume is large for lower value of initial temperature of sub$-$cooled disc (figure 3.5).

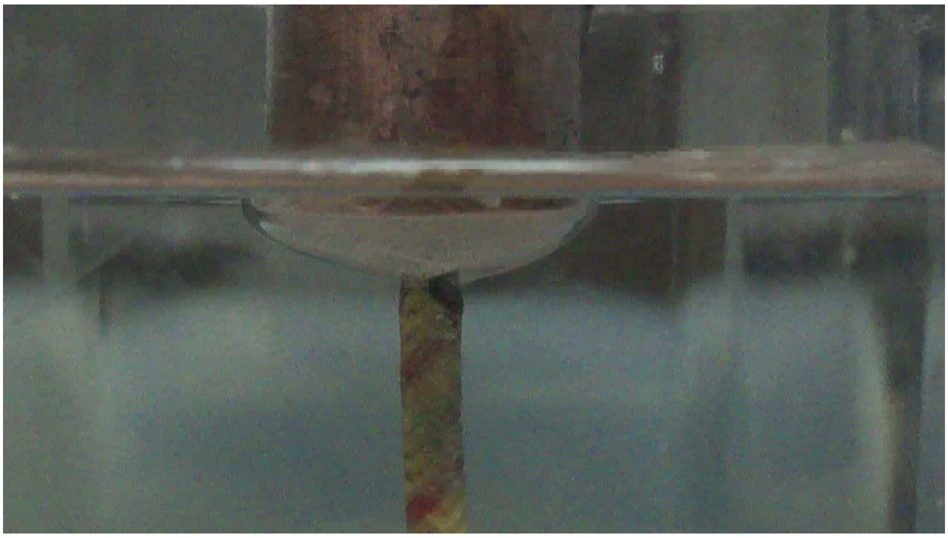

Figure 3.3: Maximum depth and width of ice for $T_i = -39°C$.

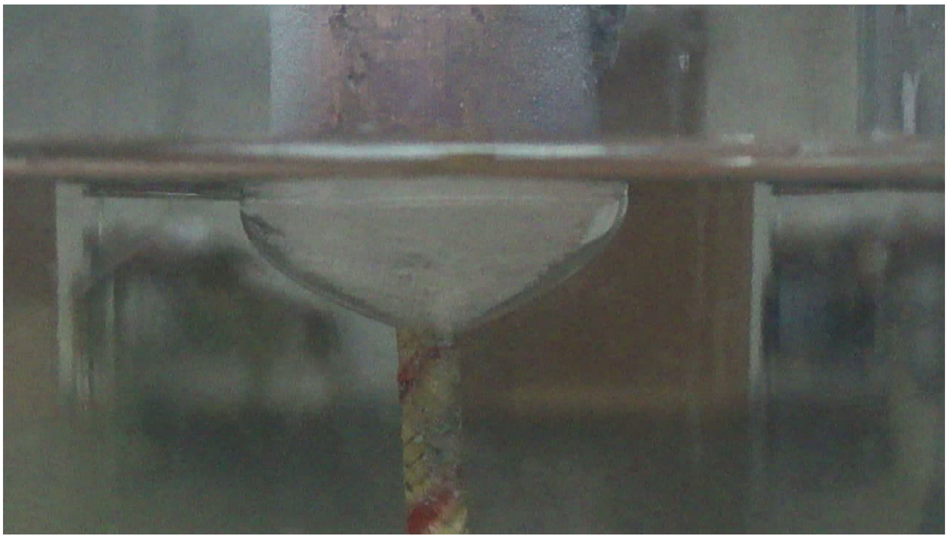

Figure 3.4: Maximum depth and width of ice for $T_i = -90°C$

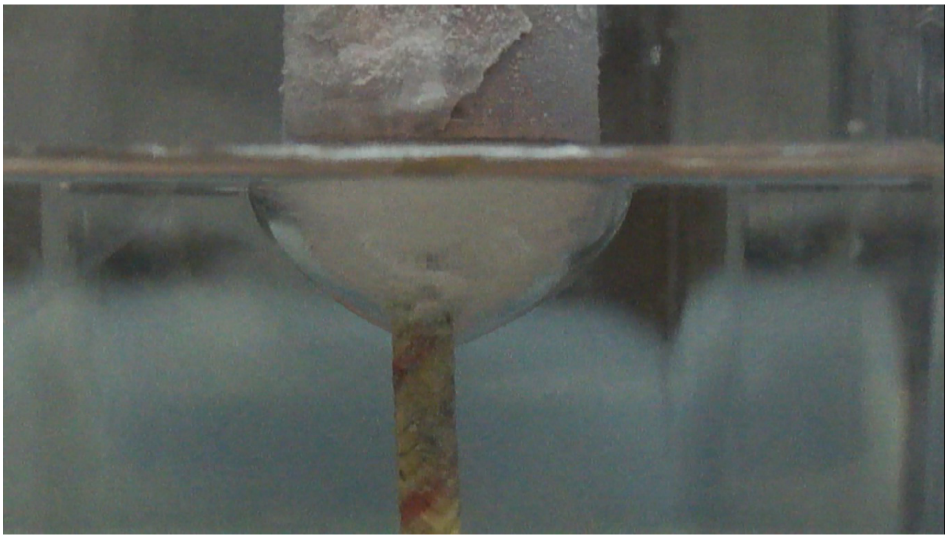

Figure 3.5: Maximum depth and width of ice for $T_i = -122°C$

The maximum depth and width of ice formation is given in the Table 3.2. It can be noticed that with the decrease in initial sub−cooled temperature of disc, the width and the depth of ice ball increase. However, the increase in depth of ice ball is more pronounced as compared to the increase in its width. It is interesting to notice that when the initial temperature of sub−cooled disc is lowered by 2.3 folds from $-39°C$ to $-90°C$ the depth of ice ball is also increased by almost 2.3 folds from 4.122 mm to 9.342 mm. But, this increase is not in proportion when the initial temperature is further lowered to $-122°C$. The thermal conductivity of ice increases with the decrease in temperature and hence the heat transfer is more rapid when the initial temperature of disc is $-122°C$ as compared to the heat transfer when the initial temperature of disc is $-90°C$. Consequently, the increase in depth of ice ball is not in proportion to the decrease in the initial temperature of sub−cooled disc.

Table 3.2: Maximum penetration when sub−cooled disc is exposed to water

Temperature ($°C$)	Width of ice-front (mm)	Depth of ice-front (mm)
−39	20.921	4.122
−90	23.026	9.342
−122	24.429	10.526

3.3 When sub−cooled Zacarian disc is exposed to gel

Figure 3.6 presents the temperature profile of the sub−cooled Zacarian disc when exposed to gel with its initial temperatures of $-39°C$, $-80°C$, and $-142°C$. As previously observed for the other cases, the time taken to reach the room temperature is more when initial temperature of sub−cooled disc is $-142°C$ compared to the initial temperatures of $-39°C$, $-80°C$. Also, it can be noticed that the time taken by the disc to reach the room temperature is more compared to the corresponding case when the disc is allowed to thaw in water and is less compared to the corresponding case when the disc is allowed to thaw in air. It should be noted that skin tissue is mimicked by a gel consisting of 0.2% agarose in distilled water. The typical value of thermal conductivity of such gel is higher than the thermal conductivity of air and is comparable to the thermal conductivity of water but is little bit lower. Figure 3.6 indicates the temperature profile of the sub−cooled Zacarian disc when exposed to gel. The figure 3.7, 3.8, 3.9 indicates the front view of formation of depression for different initial sub−cooled temperatures $T_i = -39°C$, $-80°C$, $-142°C$. The figure 3.10, 3.11, 3.12 indicates the top view of formation of depression for different initial sub−cooled temperatures $T_i = -39°C$, $-80°C$, $-142°C$. We can notice that as the initial sub-cooled temperature of the disc increases the formation of depression also increases.

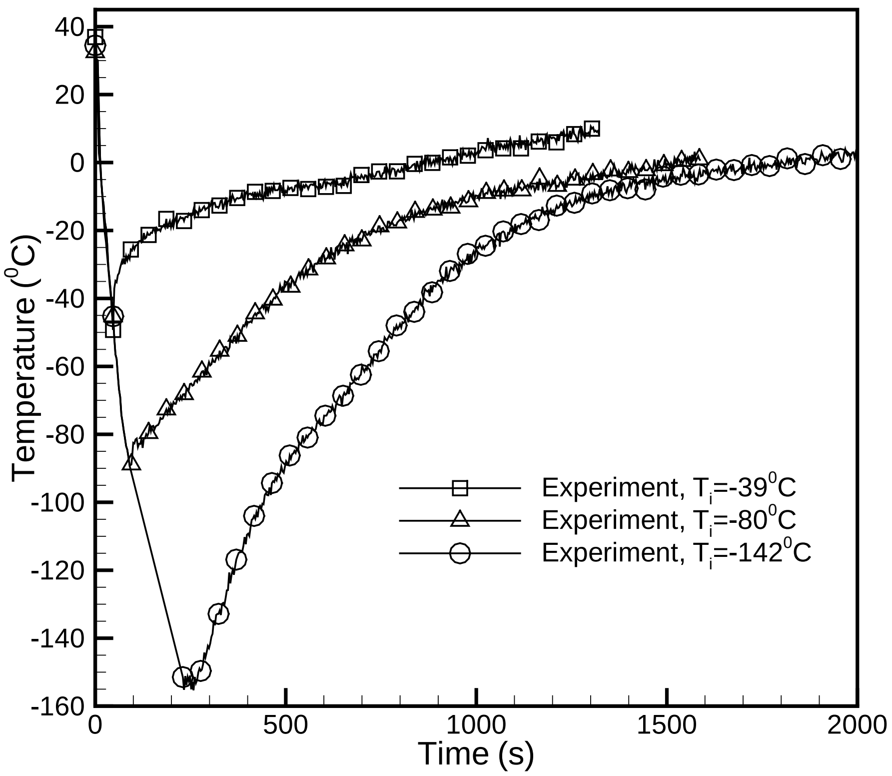

Figure 3.6: Temperature profile of sub−cooled Zacarian disc when exposed to gel

When the sub−cooled disc is brought in contact with the gel, the initiation of ice formation starts and ice ball thus formed grows in time till it acquires a maximum value. A depression is observed on the surface of gel which shows the heat affected zone. The figures 3.7−3.9 show the front view of the depression for different initial sub-cooled temperatures of $T_i = -39°C$, $-80°C$, and $-142°C$. The figures 3.10−3.12 are the top view of the depression for different initial sub−cooled temperatures of $T_i = -39°C$, $-80°C$, and $-142°C$. It should be noted, from figures 3.7−3.9, that the depth of depression is less compared to the corresponding depth of ice formation for the case of water and reverse is true regarding width of depression (figures 3.10−3.12).

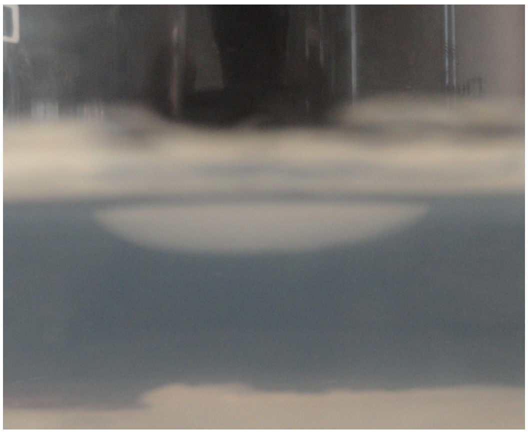

Figure 3.7: Front view of the depression for $T_i = -39°C$

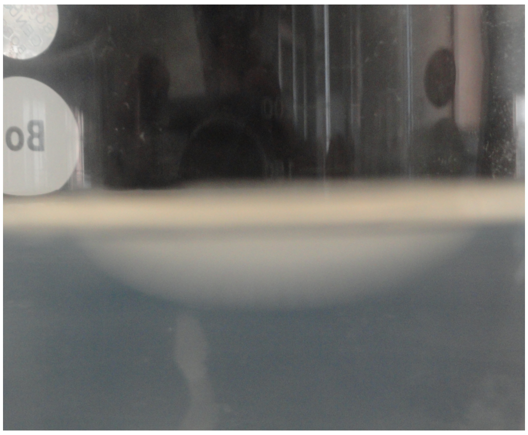

Figure 3.8: Front view of the depression for $T_i = -80°C$

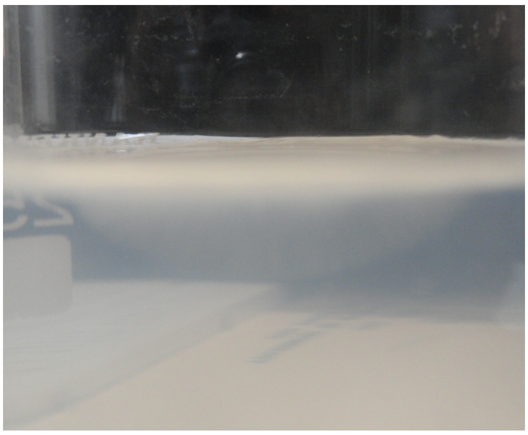

Figure 3.9: Front view of the depression for $T_i = -142°C$

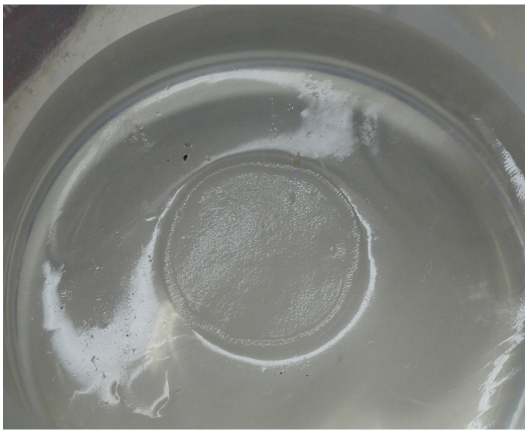

Figure 3.10: Top view of the depression for $T_i = -39°C$

Figure 3.11: Top view of the depression for $T_i = -80°C$

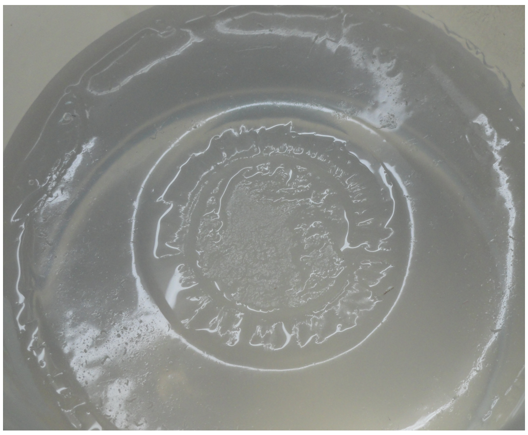

Figure 3.12: Top view of the depression for $T_i = -142°C$

3.4 Comparison of Temperature profile of sub−cooled Zacarian disc when exposed to different media

The heat transfer characteristics of thawing of sub−cooled Zacarian disc in air, water, and gel for an initial sub−cooled temperature of $-40°C$ is shown in Figure 3.13. From the figure it can be noticed that the time taken to reach the room temperature is different for different media; it is more for air followed by gel and water. This is due to the thermal conductivity of the media. Air is having a low thermal conductivity of $0.0257W/mK$ compared to that of gel (0.3 W/mK) and water ($0.6W/mK$). Also, it is interesting to observe that when the sub−cooled disc is brought in contact with the gel and water there is sudden increase in the temperature of the disc as compared to that of the air. The reason is quite obvious; the thermal conductivity plays a vital role in deciding the heat transfer characteristics of thawing process.

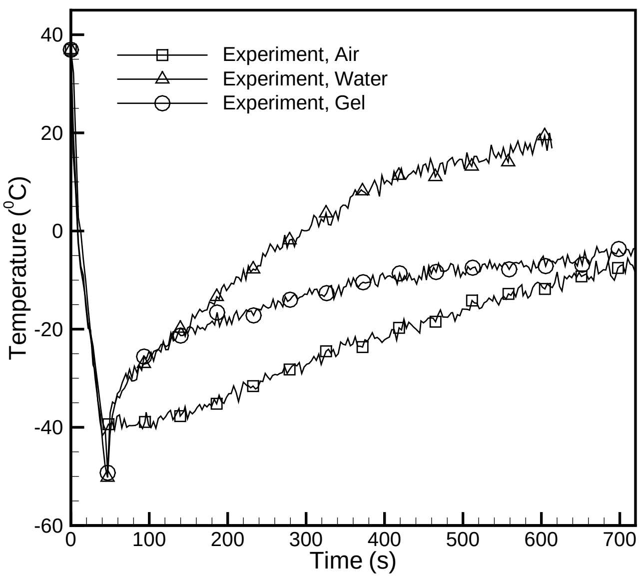

Figure 3.13: Comparison of Temperature profile of sub−cooled Zacarian disc when exposed to different media

3.5 Conclusion

In the present investigation, heat transfer characteristics during cryoablation has been studied. The overall heat transfer coefficient of Zacarian disc in different media has been investigated experimentally and predicted numerically. Maximum penetration and depth of ice formation have also been studied when the sub$-$cooled disc is exposed to water. The overall heat transfer coefficient between the disc and air was found to be $19.5 W/m^2K$ while between the disc and water was found to be 65.5 W/m^2K. In dermatology, heat transfer rate of the disc at the skin surface plays a crucial role for the necrosis of the tumour while applying the cryogen.

3.6 Future Work

Agarose gel can be replaced by any other material which mimics the tissue more realistically. In our system we are not considering about the blood perfusion and metabolism of the tissue, so if a system is designed which considers the effect of blood perfusion and the metabolism will give a more realistic result. Animal model can also be used to obtain even more realistic result. Instead of Zacarian disc, cryospray can also be used for the treatment of tumours.

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